REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 8, 1994	FINAL 1/1/92 - 12/31/93

4. TITLE AND SUBTITLE
Modeling and Parameterization of Gravity Wave Breaking, Interactions, and Instability Processes in the Lower and Middle Atmosphere

5. FUNDING NUMBERS
F49620-92-J-0138

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AFOSR-TR-95-0217

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8. PERFORMING ORGANIZATION REPORT NUMBER
153-1607

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR /NM
110 Duncan Avenue, Suite B115
Bolling Air Force Base, D.C. 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-92-J-0138

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

See Attached

Accesion For	
NTIS CRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

19950331 126

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

FINAL TECHNICAL REPORT

1. Title: Modeling and Parameterization of Gravity Wave Breaking, Interactions, and Instability Processes in the Lower and Middle Atmosphere

Agency: Air Force Office of Scientific Research

Grant Number: F49620-92-J-0138 (also AFOSR-91-0026)

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2. Research Objectives

The goals of this research were to address two sets of problems relating to gravity wave effects in the lower and middle atmosphere. One approach was intended to apply analytic and pseudo-spectral collocation techniques for studies of wave excitation, instability, dissipation, and interaction processes thought to play important roles in the circulation, structure, and variability throughout the atmosphere. A second effort was intended to apply our current understanding of the spectral character of the atmospheric motion field to the development of a parameterization scheme for the most important wave effects in large-scale models ofthe atmosphere. As seen below, these goals were accomplished.

3. Research Results

The contributions made in each of the major areas of proposed research are described separately below. These include analytic source studies, gravity wave instability modeling, and parameterization development.

a. analytic gravity wave source studies

Our studies of gravity wave sources used Fourier integral and Green's function techniques to assess the potential for gravity wave generation by sources with relatively large spatial scales. This approach was taken as most previous efforts have

focussed on excitation of gravity waves at relatively smaller scales, despite observational evidence suggesting a clear dominance of the energy within the gravity wave spectrum by motions with large scales and low frequencies.

Our first effort addressed excitation by geostrophic adjustment in two and three dimensions. In each case, it was found that this process can excite waves with low frequencies at spatial scales in reasonable agreement with observations near the stratospheric jet, where much of this activity is expected to occur. These results were reported by Fritts and Luo (1992) and Luo and Fritts (1993).

A second effort addressed a source that has been the subject of study for many years, but which until now was not treated in a quantitative manner. This is the possible excitation of gravity waves by a solar eclipse. Our study defined the 3-D wave field resulting from such a forcing and defined the altitudes where the maximum responses were expected. This effort was described by Fritts and Luo (1993).

b. modeling achievements

Under AFOSR support, we have developed 2-D and 3-D nonlinear, compressible pseudo-spectral collocation codes in association with Norwegian colleagues and applied them in studies of gravity wave breaking, instability, and turbulence generation relevant to the middle atmosphere. The code capabilities and the results obtained are summarized below.

Our initial gravity wave breaking simulations focussed on a wave motion with a high intrinsic frequency in order to limit the computer resources required to describe the evolution. We also performed parallel simulations in two and three dimensions in order to quantify the different influences on the incident wave amplitude and fluxes and to assess the validity of the 2-D results. Our simulations revealed dramatic differences in the two evolutions, suggesting that gravity wave instability is inherently 3-D and that 2-D models are unable to follow the physics of the wave breaking process or predict the influences on wave amplitudes, transports, or turbulent mixing. A comparison of the 2-D and 3-D results and an assessment of the instability structure and its effects were provided by Andreassen et al. (1993) and Fritts et al. (1993). Vortex breakdown and the subsequent evolution toward smaller, more isotropic scales were discussed by Isler et al. (1993).

Whereas instability in the 2-D simulation was confined to the plane of wave propagation (artificially), 3-D instability was found to comprise counter-rotating vortex structures aligned along the direction of wave propagation and elongated along the unstable phase of the incident wave motion. Relative to the 2-D results, the 3-D wave structure experiences rapid collapse and strong amplitude limits, supporting the convective adjustment hypothesis and suggesting that 2-D simulations are unable to describe the physics of the wave breaking process or the implications for wave and turbulent transports. Dramatic differences in the 2-D and 3-D evolutions are also

apparent in the transports of energy and momentum and in the evolution of eddy kinetic energy, providing further evidence that 2-D simulations are not suitable for studies of gravity wave interactions, instability, or induced mixing processes in the middle atmosphere.

c. development of a gravity wave parameterization scheme

An important component of the research effort funded by AFOSR was the development of a spectral parameterization of gravity wave energy and momentum fluxes for use in large-scale models of the lower and middle atmosphere. The development of this scheme and its applications to canonical mean wind and stability profiles and to tidally-varying winds were described by Fritts and VanZandt (1993), Fritts and Lu (1993), and Lu and Fritts (1993). The intent in this development effort was to create a parameterization that would conform as closely as possible to observations of the atmospheric gravity wave spectrum, its spectral shape, and its variations with altitude. This, we believed, would lead to more realistic fluxes of energy and momentum with altitude than predicted by schemes relying on discrete and noninteracting waves.

The parameterization scheme relies on a spectral description of the atmospheric gravity wave field that is largely consistent with observations throughout the atmosphere. It also accounts for wave filtering and anisotropy in a manner consistent with theory and the observations that are currently available. As a result, predicted energy and momentum fluxes are constrained realistically and are in broad agreement with observed mean and variable values. The parameterization was designed to be implemented efficiently in large-scale models of the middle atmosphere (it is presently operational in the NCAR TIME-GCM developed by Dr. Ray Roble, in the NCAR ACD middle atmosphere chemistry model, and in several middle atmosphere models in Europe). It was also designed to incorporate variable wave energies and anisotropies in response to variable gravity wave sources and source strengths in the lower atmosphere, but this variability has yet to be determined in a quantitative manner.

The spectral parameterization at present specifies mean gravity wave energies at a model lower boundary and computes the variations in wave energy, anisotropy, and energy and momentum fluxes with altitude as functions of the mean wind and stability. This assumes a uniform distribution of wave sources contributing to spectral energies at lower levels. Future improvements will include a means of describing variable wave sources at lower levels, more quantitative specification of seasonal wave variability, and temporally variable wave energy and momentum fluxes in response to tidal forcing.

4. Publications Citing this AFOSR Support

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VanZandt, T. E., and D. C. Fritts, 1993: Spectral estimates of gravity wave energy and momentum fluxes, *Coupling Processes in the Lower and Middle Atmosphere*, NATO ASI Workshop, **387**, 261–290.

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